CHAPTER 42

THE NATURAL DEVELOPMENT OF THE WADDEN SEA AFTER THE ENCLOSURE OF THE ZUIDER SEA

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ABSTRACT

The Wadden Sea and Zuider Sea used to form an internal sea which was parated from the North Sea by a chain of islands. In 1932 the Zuider Sea w enclosed by a dam 32 km in length. Owing to this, the Wadden Sea experienc changes in the normal tidal movement, the storm-surge levels and the confi guration of the bed. This article discusses the movement of water and sand the Wadden Sea and its natural development since the enclosure of the Zuid

I.INTRODUCTION

The formation of the Wadden Sea and Zuider Sea commenced about the be ginning of the Christian era when the sea broke through the coastal barrie as a result of a rising sea level. The peat and clay areas lying behind th coastal barrier where either drowned or eroded away. In this way an interr sea was created, surrounded by a low-lying clay and peat area and bounded the sea side by an intermittent line of coastal dunes. Some tidal inlets m have appeared where the coast was already broken by the mouths of rivers.

As the area of the internal sea increased, the capacity of the tidal lets also increased. This caused increased erosion and so the process was celerated. In the course of the Middle Ages the inhabitants began to stabi lise the coast-line by means of dykes. In this way a dynamic equilibrium w established between the rise in sea level and the configuration of the bec the internal sea. The transport of water and sand takes place chiefly in a system of channels which branch out strongly landwards of the tidal inlets. Between these channels lie flats and banks called the Wadden. The height c the Wadden is determined among other factors by the transport of material the sea and the level of high-water. At high-water the Wadden-flats are cc ed by water and some of the suspended material which has been brought in s to the bottom. As the water ebbs, not all the material which has settled c is carried back again, so the flats are gradually increasing in level. Thi increase slows down as the level of the Wadden approaches high-water level If the sea-level were to remain constant and the amount of material brough in were sufficient, new land would be created. Vegetation would take root the Wadden would come to lie above high-water level. The reservoir capacit of the sea would become smaller, resulting in a decrease in the size of th channels. However, if the sea-level is continually rising, the level of th Wadden will show a certain delay in response which is dependant on the qua tity of material available and the rate of rise in sea-level.

If the increase in sea-level shows fluctuations, an alternate accreti and erosion of the Wadden can occur. By "increase in sealevel" is meant th relative increase in sea-level, consisting of the absolute movement of the sea-level and the movement of the land, which may be susceptible to tector movement of the earth's crust and to consolidation of the sediments.

The geological structure of the Wadden area can be broadly described follows. Westwards of the Vlie Inlet, boulder clay has often been found at depth varying from a few meters to about 20 m under N.A.P. (Dutch Ordnance Level = mean sea level). Boulder clay at depths of less than 20 m under NA means that this area was an island during the Riss-Würm interglacial. In t

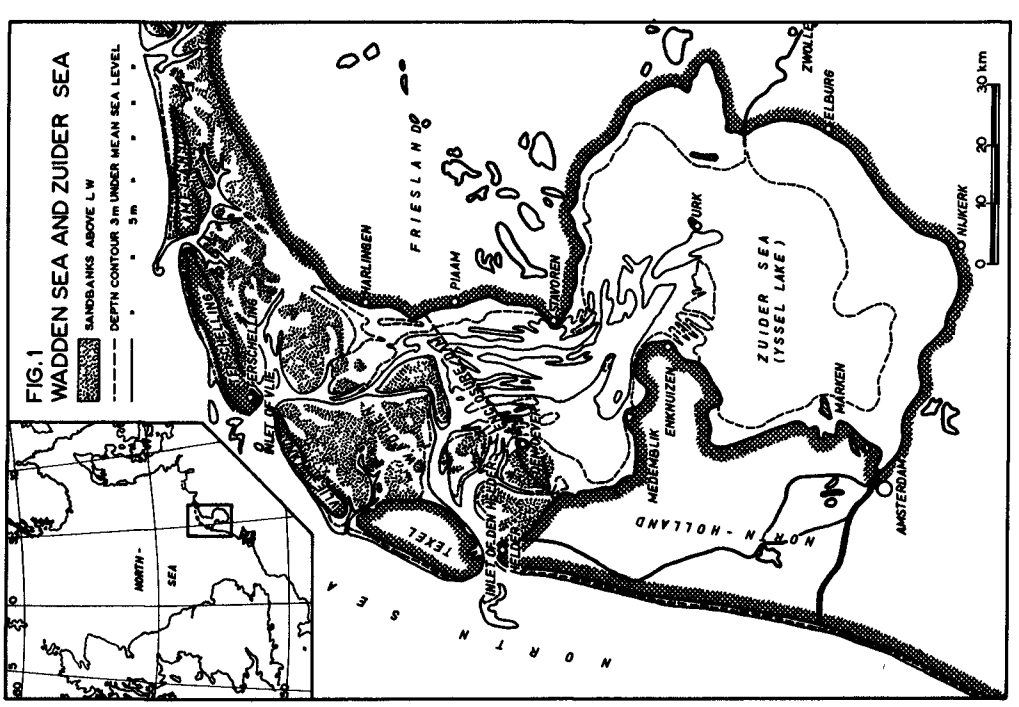

Fig. 1. Wadden Sea and Zuider Sea.

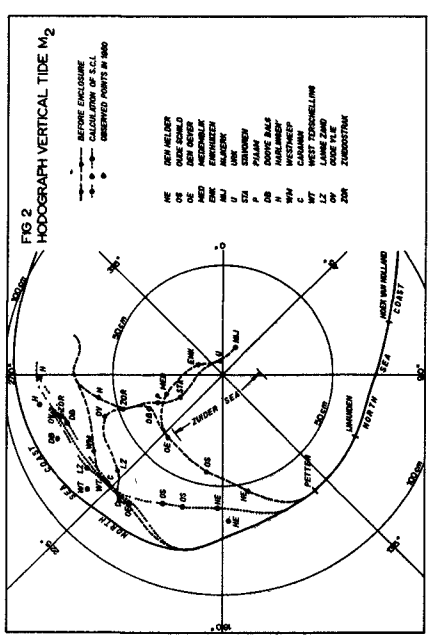

Fig. 2. Hodograph vertical tide M_2.

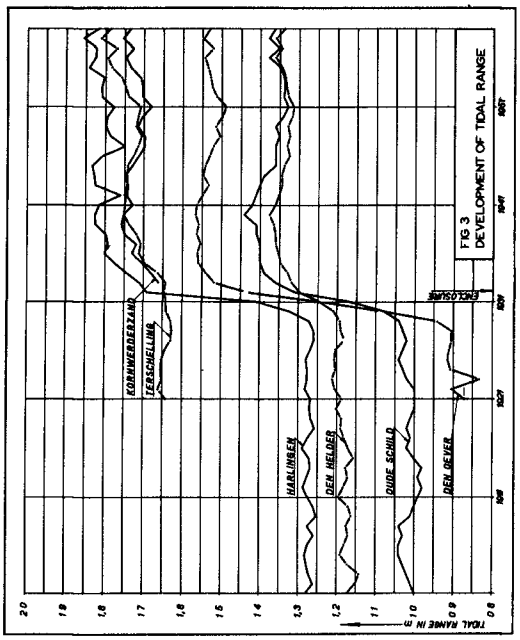

Fig. 3. Development of tidal range.

case, marine Eem deposits are not present. During the Würm glacial, low-terrace sand was deposited on the boulder-clay. At the beginning of the holocene, about 10.000 years ago, a peat layer was formed on this sand. This peat layer is referred to as "peat at greater depth". On top of the peat a early holocene Wadden deposits and old marine clay (5.000 - 2.000 B.C.). A present the old marine clay extends to 2 -2,5 m under NAP and in places it has a very low chalk content, indicating that this marine clay has at some time lain above high-water. On the old marine clay, the great Dutch peat l er was formed. In the Wadden Sea this layer has now an average thickness o about 1 m. About at the beginning of our era, erosion of the peat layer st ed. The great loss of land took place in the 13th and 14th centuries. Perh this was assisted by the digging of canals and the excavation of peat. On parts of the peat layer which were left, new marine clay or new marine san was deposited, a process which is still taking place.

Thus after the Würm glacial there were two periods with peat formatio Then the relative rise in sea-level was retarded or even changed into a te porary fall, so that the Wadden had the capacity for accretion, using the m terial available.

From about the 1st century onwards, the Wadden, which had previously creted by peat formation, were flooded and largely eroded away as a result the relative rise in sea-level.

In this way the Zuider Sea was formed. It was surrounded by land whic was protected by dykes, but which suffered from repeated flooding. During storms, the North Sea water surged through the inlets and high water level could occur as a result of the local wind effect on this shallow sea. Brea in the dykes were common and raising the level of the dykes was very expen as a result of the very long coast-line.

After the storm surge disaster of 1916, the plans for the reclamation a part of the Zuider Sea became definite and an integral part of these pla was the enclosure of the Zuider Sea. The enclosure would prevent high wate levels in the Zuider Sea and reduce the coast-line from a length of c. 250 to 30 km. The remaining part of the internal sea, the Wadden Sea, would re in open connection with the North Sea. Work on the enclosing dam began in and in May 1932 the last gap was closed. The area of the internal sea was by reduced from c. 5200 km^2 to 1500 km^2. The movement of water in the rema part would experience important alterations, chief of which would be that storm surge levels along the coast would be changed. Because of this, a co mission was set up whose task was to determine how much the enclosure woul raise storm surge levels along the coast outside the enclosing dam above w would have previously occurred (State Commission Lorentz 1918 - 1926). Thi commission, hereafter referred to as S.C.L., published a comprehensive rep on the changes which would occur in the normal tidal movement and in the s surge levels in the Wadden Sea after enclosure of the Zuider Sea.

As a result of the changes in the movement of water, the topography c the Wadden Sea would experience alterations.

In the paragraphs which follow, the normal tidal movement, the storm surges and the topography of the bed will be described.

II. NORMAL TIDAL MOVEMENT.

In the Wadden Sea and the former Zuider Sea (now the IJssel lake) tid effects are chiefly dependent on the diurnal lunar tide M_2. The amplitude the tide is not everywhere the same. See fig 2, in which the amplitude and phase of the M_2 tide are represented graphically.

Before calculating the increase in storm surge levels due to enclosur of the Zuider Sea, it was first necessary to compute the influence of the enclosure on normal tidal movement.

For this purpose the Wadden Sea and Zuider Sea were schematically represented as a network of flowing channels, separated by flats and banks, which were considered to provide storage capacity.

As tide, the sinusoidal diurnal lunar tide M_2 was considered. The cal culation was made following the single harmonic method with linear frictio In comparison with the tidal flow, fresh water flow could be neglected.

The boundary conditions were the vertical tide in the North Sea which would not be influenced by the enclosure, and the condition of zero flow a the ends of dead-end channels.

The result of the calculations for the vertical tide in a number of points is shown in fig 2. The amplitude of the vertical tide would increas landwards and in the region of the enclosing dam it would even be doubled places. The capacity of the inlets would increase considerably. The latter be clarified schematically as follows.

Without friction a standing wave would occur with a node at a 1/4 wav length λ from the closed end and an antinode at $1/2\lambda$. The "length" of the internal sea is reduced from $0,6\lambda$ to $0,2\lambda$ by the enclosure of the Zuider S This causes the flow in the inlets to increase. If friction is taken into count, the ratio of the amplitudes of the vertical tidal movement and the at the open end of a uniform channel can, for a sinusoidal tide, be descri by:

$$\frac{a_s^2}{a_h^2} = \frac{4\pi^2 b^2 u^2}{4\pi^2 + r^2\lambda^2} \cdot \frac{e^{2r\ell} + e^{-2r\ell} - 2\cos\frac{4\pi\ell}{\lambda}}{e^{2r\ell} + e^{-2r\ell} + 2\cos\frac{4\pi\ell}{\lambda}} \qquad (1$$

(see litt. 1, p. 113)

in which

a_s = amplitude of the flow
a_h = " " " vertical tide
u = velocity of propogation of the tide
λ = wave-length of the tidal wave
r = damping factor resulting from linear friction
ℓ = length of the channel
b = width " " "

The first factor in (1) is independent of the length of the canal. The sec factor is a damped oscillation about the value 1 . In the interval between $\ell = 1/2\lambda$ and $\ell = 1/4\lambda$ the value increases with decreasing ℓ. Between $\ell = 1/4\lambda$ and $\ell = 0$ the reverse is true. The "lengths" of the Wadden Sea and Z der Sea are respectively $0,2\lambda$ and $0,4\lambda$. By the enclorues of the Zuider

Sea the length is reduced from $0,6\lambda$ to $0,2\lambda$. Hereby, the ratio a_s^2/a_h^2 increases.

From the comprehensive tidal calculation it appeared that the increase was so great that it was feared that the tidal inlets would come into a dar gerous situation. This was one of the considerations which led to the enclosing dam being constructed somewhat to the north of where it was originally designed. By this means the danger to the inlets could to some extent be reduced. The length of the Wadden Sea then comes further under the $1/4\lambda$ so that the ratio a_s/a_h becomes smaller.

The increase in the capacity of the Inlet of Den Helder was reduced fi 30 % to about 25 % in this way.

During and after the enclosure, the development of the tidal movement was carefully observed. The results of the calculations of the S.C.L. appe ed to be in very good agreement with the actual development. In fig 2 the ual vertical M_2 tide has been drawn for several observation stations.

The adaptation of the tide to the new situation in some parts of the Wadden Sea took place more quickly than in others. This is partially depen on the adaptation of the channel system. As an illustration, fig 3 shows t tidal range before, during, and after enclosure for a number of observatio stations.

In this figure can also be seen the influence of the variation in the inclination of the moon's orbit to the equator. The period of the variatio is 18 2/3 years. Maxima occur in 1922, 1941 and 1960 and the influence on tidal range amounts to 1 1/2 - 2 %.

Correction of the observations since 1933 results in a tidal range wh decreases for Den Oever and Oude Schild, increases for Harlingen and Tersc ling and is almost unchanged for Den Helder and Kornwerderzand. This will referred to in chapter IV.

The regular flow measurements have also largely confirmed the results the tidal calculations.

Another important consequence of the enclosure was the formation of a watershed between the two main inlets of Den Helder and The Vlie.

With an open Zuider Sea, the tidal streams coming from these inlets w directed towards the Zuider Sea. Since the enclosure, the streams meet eac other in a region near Harlingen, and a watershed has been formed. Because shoaling usually takes place at a watershed, it was important to know whet and, if so, where, there was a chance of shoaling which could be a hindrar to navigation. The tidal calculation gave useful information about this tc The position of the watershed is very much dependent upon the slowly devel ing system of channels. The situation in this area has still not come to r and the development is regularly surveyed by means of water-level recorder soundings and flow measurements.

The work of the S.C.L. has thus proved that even for such a complicated ar as the Wadden Sea and Zuider Sea tidal calculations can be performed with success.

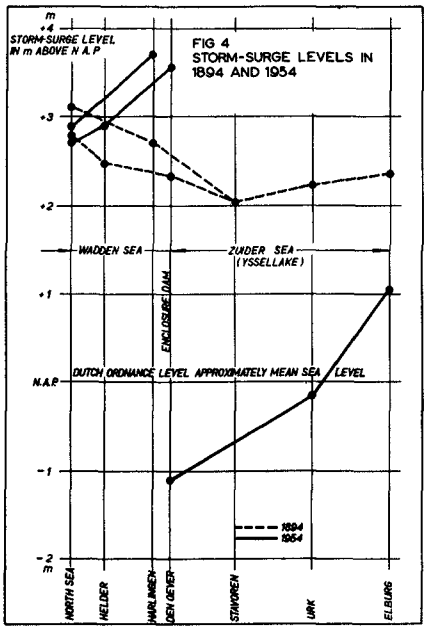

Fig. 4. Storm-surge levels in 1894 and 1954.

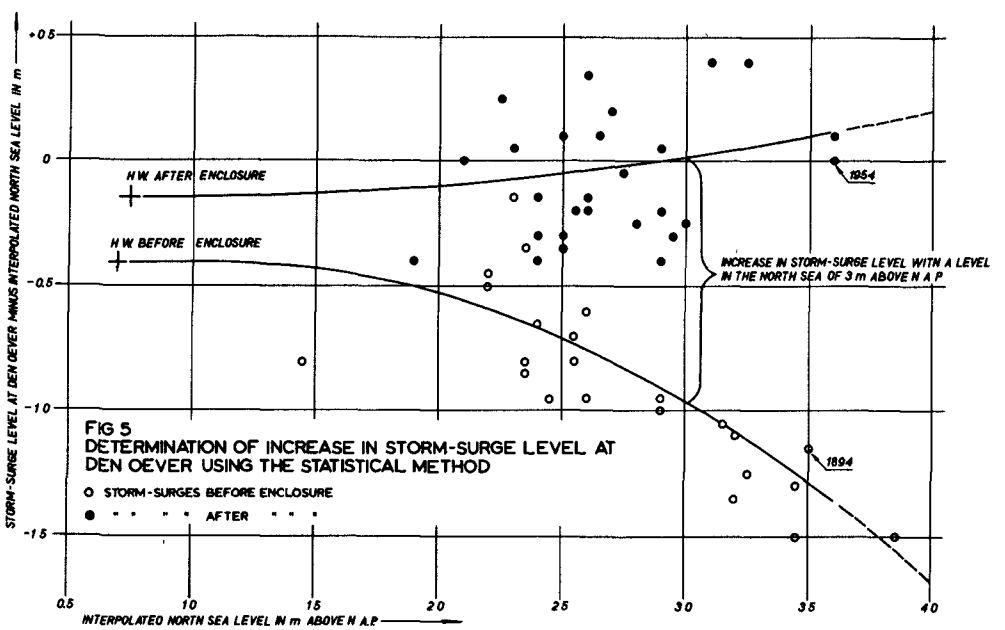

Fig. 5. Determination of increase in storm-surge level at Den Oever using the statistical method.

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III. THE STORM SURGES

Northwesterly gales increase the water levels along the Dutch coast. As a result of the difference in head and the action of the wind, water flows through the inlets into the Wadden Sea and formerly also into the Zuider Sea. If the storm lasts for long enough, a state of equilibrium is reached between the force of the wind and the slope of the water surface. If the state of equilibrium is not reached, the maximum water level is not only dependent on the gale-force but also on the degree to which the basins behind the inlets are filled. The area of the Wadden Sea and Zuider Sea together was so big relative to the capacity of the tidal inlets, that even prolonged storms usually fail to produce complete filling right up to the equilibrium condition. In this way the Zuider Sea helped to reduce the highest water levels in the Wadden Sea.

After the enclosure the area was reduced from 5200 to 1500 km^2 and the capacity of the inlets is sufficient to cause complete filling of the Wadden Sea if the storm is prolonged. This can be shown by means of fig 4 in which the storm surge levels in the Wadden Sea (and Zuider Sea) are represented for the storms of 1894 and 1954, which were similar. It is clear from the slope of the lines that the situation in 1894 was still far from equilibrium. In 1954 equilibrium was almost attained. As illustration, several water levels in the IJssel Lake have been drawn in for 1954 to demonstrate the influence of enclosure in lowering the storm surge levels in the IJssel Lake (former Zuider Sea).

From fig 4 it also appears that the levels at Den Helder and Den Oever in 1954 were respectively 0,4 and 1,1 m higher than in 1894.

The task of the S.C.L. was now to predict how much the known storm surge levels would be raised as a result of the enclosure. It calculated the rise to be expected by various methods. In all cases the observations made of previous storms were used. There was no question of extrapolation of frequencies of storm surges because the aim of the enquiry concerned only the rise in known storm surge levels. The sea defences could then be raised so that the same degree of safety against breaching would exist as before the enclosure. The height required for the enclosing dam could also be determined from the enquiry. At the time of the S.C.L. the heights of dykes were not determined by using frequencies, but were based on the highest known storm surge level at that point.

The storm of 1894 was taken as the design condition, as it caused the greatest flow from Wadden Sea into Zuider Sea. For this storm very extensive stationary calculations were made, again using a Wadden Sea schematized as a network of channels. In addition, some trial calculations were performed using a method of integration by power series. It was not necessary to base this latter calculation on a permanent condition so that, in addition to the forces due to friction and hydraulic gradient, the momentum could also be taken into account. The calculation was, however, very cumbersome and could only be applied to a very much simplified network of channels. It was used to make corrections to the results of the stationary calculation. In general, the results of the non-stationary calculation were higher than those of the stationary, especially near the inlets.

After the storm surge disaster of 1953, the "Delta Commission" was set up, which in 1955 had to construct the frequency lines for the storm flood surges along the Dutch coast. These frequency lines had to show what water level was attained with a certain frequency at all points along the coast. The aim of this was to be able to design a height for a sea-defence which

would guarantee a degree of safety suited to the value of the area lying hind. For this, the frequency lines of the observation stations in the W Sea had also to be used. Because the period of observation since the enc ure of the Zuider Sea amounted to only 23 years and was therefore too sh for estimating very infrequent levels, the data from before 1932 had to treated in such a way that it fitted into the frequency lines found afte closure.

At the same time, it was possible to use this research to test the diction of the S.C.L. against actual conditions. Until then this had only done approximately for individual storms.

For the frequency lines, all storms from before the enclosure had t considered; it was not sufficient to calculate the rise for a few chosen storms.

The following methods were used for this:

1. STATISTICAL METHOD.

For each storm, the North Sea level "N" is derived from observation coastal stations which lie sufficiently far from the region influenced b enclosure. This derived North Sea level is therefore independent of the closure of the Zuider Sea.

The difference between N and the observed storm surge level at a ce station is plotted graphically against N. Two lines are then drawn; one through the points representing storms before the enclosure and one thro points from after the enclosure. The ordinate between these two lines gi the rise in storm surge level at a certain station as a function of the surge level in the North Sea outside the inlets.

In this fashion, all observations from before the enclosure can be verted to the situation after enclosure.

2. LINES OF RELATIONSHIP.

In this method each of the stations influenced by the enclosure is pared with a station not subject to such influence. The storm surge leve the two stations are plotted graphically, one against the other. As befo lines are drawn through points which represent levels before and after e closure. The ordinate between the two lines gives the rise at a certain ion as a function of the storm surge level at the other station. A Wadde station can of course be compared with more than one uninfluenced statio

Both methods have rather serious disadvantages. One of the most ser is that in this analysis, the duration of the storm is neglected and it this duration which is so important in connection with the filling of th Zuider Sea. At a station in the neighbourhood of the enclosing dam a pro ed storm before the enclosure can lead to the same water levels as a sho storm after the enclosure. In the analysis described above, no rise in s level would be noticed.

The points in the graphs therefore show a rather large scatter. It only the more or less uniform behaviour of the storms which prevents the scatter from being even greater. Fig 5 has been appended as an example o such a graph. In it, the rise in storm surge level for Den Oever has bee determined by the statistical method.

Finally, a hydraulic calculation was made for one particular storm usir a semi-permanent iteration method. This calculation served to give a better understanding of the course of the storm surge and to verify the results of the above mentioned methods for this particular storm.

Some results of the various calculations for three stations are given i Table 1.

TABLE 1.

Station	Rise in storm surge level in meters for a design storm as defined by the S.C.L.			
	S.C.L.	Statistical method	Lines of relationship	Hydraulic computation
Den Helder	0,42	0,7	0,95	0,55
Den Oever	1,08	1,4	1,15	-
Harlingen	0,64	0,75	0,7	1,0

The values given by the S.C.L. are in general too low. In the correctic of the stationary calculation incomplete account has been taken of the resul of the exact calculation. The latter gave deviations from the stationary cal culations which were much bigger in the inlets than along the coast of the Wadden Sea.

Afterwards, it appeared that the behaviour of the 1894 storm was such that it caused relatively high levels in the inlets so that the rise predict ed for the 1894 storm agrees, but for most other storms with the same North Sea level, the predicted rises would be too low. This is not a consequence c the method of calculation used but is dependent on which storm is chosen to define design conditions. The corrections which were applied to the final results with regard to other storms are wrong. The values found by means of the statistical method and the lines of relationship will deviate from reali for a certain storm, but they give a good approximation when it is a questic of correcting a large number of storm surge levels.

The hydraulic method is not capable of being applied to a great number of storms because of the great amount of work required.

Research in a hydraulic model, although possible in principle, would al so become too protracted to be applied in practice.

IV.TOPOGRAPHY OF THE BED.

GENERAL CONDITIONS.

A possible explanation of the mechanism of the Wadden Sea is as follows Before the enxlosure of the Zuider Sea, there existed in the Wadden Sea a certain relationship between the height of the Wadden, the rise in sea level and the transport of sand from the North Sea. The system of channels was adapted to the storage capacity of the region. If the transport of sand were to decrease, the increase in bed-level would be delayed with respect to the rise in sea-level, or in other words the delay in response would be greater. The storage reservoir would increase and thereby also the capacity of the in

lets and the system of channels behind, and this would continue until a r equilibrium was reached. The delay in response of the Wadden need not be same at every point. There are reasons for believing that the build up ir region of the inlets takes precedence over that further back in the Wadc Sea. Material which is brought in through the inlet will settle out in tl direct neighbourhood rather than further back. Furthermore, the wave move further back in the Wadden Sea is stronger than in the lee of the islands The height of the Wadden with respect to H.W. therefore decreases landwar from the inlet.

The bed of the Wadden Sea consists chiefly of fine sand. Silt hardly settles out at all; the Wadden are too exposed to the action of wind waves for this to occur. Only in sheltered corners and with artificial means, s as the reclamation works along the Frisian and Groningen coast, can the s settle out. Also the digestive processes of shell-fish cause some silt tc settle.

All sediments have their origin in the North Sea, as has been shown petrographic research. River sand or river silt is not found. Silt can al originate in clay layers in the Wadden Sea itself which become exposed anc eroded through the movement of channels.

The material for building up the bed must therefore come into the Wa Sea through the inlets. It may come from littoral drift, by erosion of tl North Sea coast and perhaps also directly from the bed of the North Sea. littoral drift alone is, according to van Bendegom (litt. 2), insufficier satisfy the sand hunger of the Wadden Sea.

During the last 50 years the relative rise in sea level amounted to 2 mm per year. For an area of 1500 km^2, the amount of sand required is 3×10^6 m^3 per year.

The stretch of coast on the North Sea which is influenced by the Wac Sea loses, owing to erosion, an amount of sand roughly estimated at about 1×10^6 m^3 per year. The amount of material which enters the Wadden Sea t the inlets is unknown. With the present day instruments and measurement t niques, it has proved impossible to measure a resultant sand- and silt-tr port with sufficient accuracy.

The amount of silt which arrives by discharge from the IJssel Lake i relatively insignificant, about 0.5×10^6 m^3 per year.

The enclosure of the Zuider Sea has had a big influence on the proce described above. As a result of enclosure, over almost the whole of the v Wadden Sea (as far as the Terschelling watershed), high water level has r from 0,1 - 0,3 m. This has the same effect as a sudden rise of a similar in the sea level. The sand hunger of the Wadden Sea has increased strongl a result.

Since the enclosure, bed-levels have been regularly sounded, especia in a strip 10 km wide along the enclosing dam.

A calculation of the difference in bed-level for this area over the period since enclosure, shows that, after correcting for the rise in sea level, an average of $9 - 10 \times 10^6$ m^3 per year of sand and silt is laid dc this is equivalent to 2 cm per year. The greater part of this material ha been deposited in the channels which have been blocked by the enclosing c

(7 - 8 x 10^6 m^3 per year). The sand flats, in so far as they are found in this area, have even become lower - about 1 cm per year. It must however be noted that a great proportion of the flats considered lie in the region of the Dove Balg, where the movement of water has increased considerably since the enclosure. The enlargement of the cross-sectional area available for fl may perhaps be sought outside the limits of the Dove Balg and extending ove the flats on either side.

There is also a possibility that material is disturbed by wave action and transported to the dead-end channels where it settles out and is thus taken out of circulation.

Since enclosure the transport of sand and silt to the 10 km strip considered has been greater than that which would correspond with the rise in sea level. Actually, it is even greater than would be necessary to keep up with the rise in sea level over the whole Wadden Sea. The origin of the material is not clear. It may be partly derived from the rest of the Wadden S but a large part must have come from the North Sea.

An approximate survey of the height of the flats behind Texel and Vlie land has shown that since the enclosure, these flats are becoming lower by an average of 2 - 3 mm per year. From this, a quantity of sand would be released of about 0,5 x 10^6 m^3 per year. If the other flats in this area beh similarly, then about 10^6 m^3 of sand per year can be taken up.

An attempt to establish a sand and silt balance for the western Wadde Sea gives the following result:

Settling in the strip c. 10 km wide, north of enclosing dam	10 x 10^6 m^3/year	
Taken up from the flats to the north of this area		1 x 10^6 m^3/year
Transport along the North Sea coast, according to van Veen (litt.8) amounts to 1 - 2 x 10^6 m^3 per year. If almost all of this enters the Wadden Sea, then we have		1 x 10^6 m^3/year
Coastal erosion can supply a maximum of		1 x 10^6 m^3/year
From erosion of the external deltas, maximum		1 x 10^6 m^3/year
IJssel Lake silt		0,5 x 10^6 m^3/year
Directly from the North Sea, errors in the above estimates and unknown sources		5,5 x 10^6 m^3/year
	10 x 10^6 m^3/year	10 x 10^6 m^3/year

From the above data and assumptions, about 8 x 10^6 m^3/year enters the western Wadden Sea through the inlets. The capacity of the inlets of Den Helder and the Vlie together amount to 2 x 10^9 m^3. If it is assumed that half of the transport takes place over the bed and the other half in suspe ion, then a difference in concentration of 4 - 5 mg/l would be sufficient carry 4 x 10^6 m^3/year of suspended solids into the Wadden Sea. As the aver content is 40 mg/l, the accuracy of measurement would have to be better th 10 % to be able to show this resultant transport. Bed transport measuremen are even less accurate than measurements of transport in suspension. The c clusion is therefore that in the western Wadden Sea a large amount of mate is deposited, the origin of more than half of which is unknown. Measuremen of transport in the inlets cannot provide any information because of the r

Table 2

Hydrographical data of Wadden Sea

nr	station name	mean tidal conditions: max.velocity in m/sec flood	max.velocity in m/sec ebb	max.discharge in 10^3 m^3 flood	max.discharge in 10^3 m^3 ebb	tidal priem in 10^6 m^3 flood	tidal priem in 10^6 m^3 ebb	area of cross-section in m^2	C $m^{\frac{1}{2}}$/sec	τ_{max} N/m^2	$u_{*\,max}$ m/sec	bed material 1)	development of cross-section 2)
1	Marsdiep	1,8	1,6	72,0	64,0	930	1020	54.000	53	6,4	0,08	I, II	1,04
2	Texelstroom W	1,4	1,4	46,0	43,0	615	710	44.500	53	3,8	0,06	II, III	0,88
3	Wisrbalg	0,8	0,6	-	-	-	-	3.200	50	3,9	0,05	II, III	0,48
4	Dove Balg O	1,2	0,8	16,0	10,8	170	170	15.200	50	4,4	0,06	I	1,26
5	Inschot	0,8	1,0	8,4	7,0	120	125	10.700	50	2,5	0,05	II	0,67
6	Blauwe Slenk	1,0	0,9	8,2	5,9	130	100	9.000	50	3,3	0,06	I, II	1,16
7	Pannengat	"	-	7,0	7,5	115	135	8.000	50	3,5	0,06	I	
8	Vlietstroom	1,3	1,2	31,5	25,5	475	425	25.000	52	5,9	0,07	I, II	1
9	West Meep	1,6	1,1	21,0	22,0	350	375	18.500	52	5,2	0,07	II	1,28
10	Vlierede bij Caranan	1,3	1,1	-	-	-	-	40.000	53	6,0	0,08	I	1,20

1) Classification - I - coarse sand, often with gravel and shell remains
II - sand with very little or no silt
III - half sand - half silt to sand with little silt

2) Development of cross-section = $\frac{\text{area in 1950-1960}}{\text{area before enclosure}}$

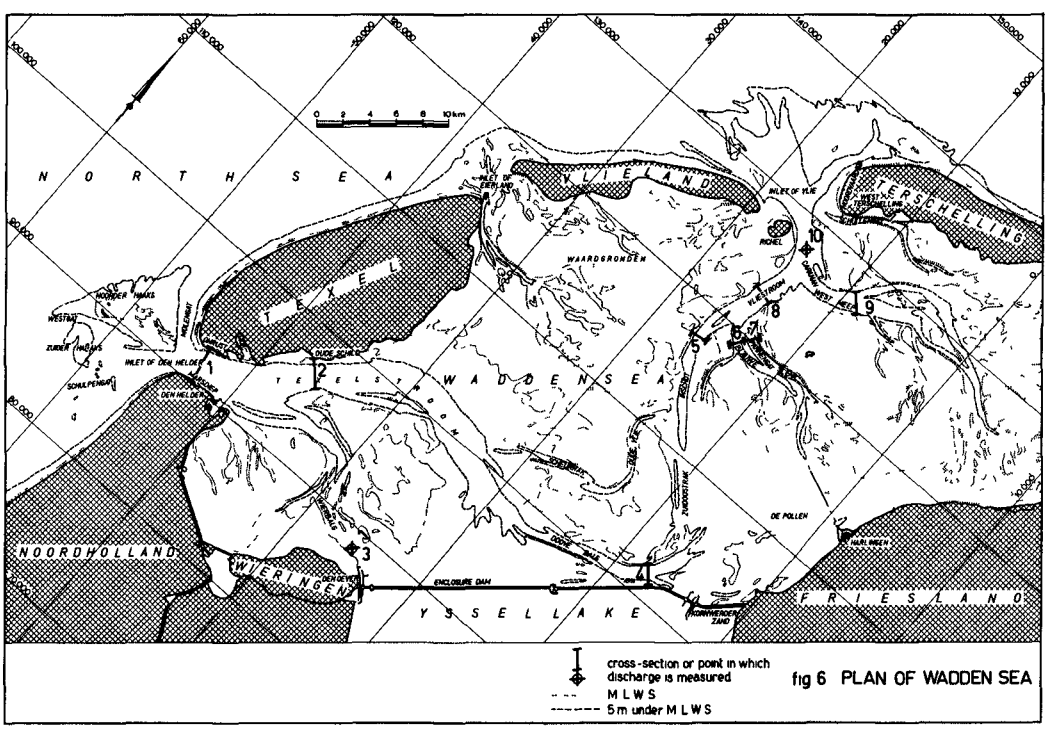

fig 6 PLAN OF WADDEN SEA

Fig. 6. Plan of Wadden Sea.

quired accuracy of measurement. The only available method appears to be t establishment of sand and silt belances over long periods using soundings beach measurements over the whole area which is influenced.

Special considerations (see fig 6).

The systems of channels running from the Inlet of Den Helder and the let of Vlie meet each other in an extensive area of zero horizontal tide the neighbourhood of Harlingen. Formerly, both systems ran approximately rallel to the Zuider Sea. A resultant water transport from the Inlet of D Helder to the Inlet of Vlie hardly occurs. For both inlets, the volume of ebb is almost equal to that of the flood.

The connections between the two channel-systems originated in the ph lag between the tide in the inlets of Den Helder and Vlie.

After the enclosure, two connections remained north of the enclosing namely the Dove Balg and the Scheurrak - Oude Vlie channel.

The tide comming from the Inlet of Den Helder is so much earlier tha that coming from the Inlet of Vlie that both connections are entirely und the influence of the former inlet. The flood in the Scheurrak meets that the Vlie near the confluence of the Oude Vlie with the Inschot. Because o this, the flows in the former channel have somewhat decreased.

The Dove Balg however, at present, carries a large quantity of water the direction of Harlingen and the cross section of this channel has incr appreciably since enclosure.

This growth in cross section causes the tide on the east side to arr earlier, so that the area of influence is still increasing. Moreover, beca of this, the tidal range in the area round Harlingen is still increasing slightly. From fig 3 it is seen that for Harlingen, after correction for influence of the inclination of the lunar orbit, there is an average incr in the tidal range of 3 cm in 20 years. Because of the growth of the Dove the tidal range at Oude Schild is decreasing, as also can be seen in fig The earlier appearance of the tide at both stations is in agreement with

The channels to the north and east of Wieringen, which formerly carr water to the Zuider Sea, now cater for the filling of only a small area r Wieringen. Their dimensions are therefore rapidly diminishing. As a resul this, the tidal range at Den Oever has somewhat decreased since the enclo (see fig 3).

The Texelstroom remains almost unchanged, except for the eastern par The discharge here has also varied little since the enclosure.

The Marsdiep, the throat of the Inlet of Den Helder, also hardly var in cross section, although the max. discharge here has increased by about The southern shore has been stabilised and the depth is very great, in pl 45 m. The bed consists of coarse sand. It is not known why the cross sect area remains practically constant.

The channels which are influenced by the Inlet of Vlie are, with the exception of the Inschot, becoming larger. This is a consequence of the i creased tidal movement in this area, which was predicted by the S.C.L.

The tide at Terschelling has been increasing rather rapidly since en-

closure (about 7 cm in 20 years). This would indicate an influence of the i let between Terschelling and Ameland in which the tidal movement is stronge than in the Inlet of Vlie. Since enclosure, the tide at Terschelling arrive earlier. This is in contradiction to the assumption made above. The actual cause of the behaviour of the tide at Terschelling is unknown.

The Inschot has not grown because the discharge here has not increasec as a result of the watershed which has formed near by.

An interesting area is the Pollen. This is a basin with an almost hori zontal bed with several very shallow channels. The explanation of the origi of this area (where actually a rather high flat might have been expected) i possibly as follows. The area was formed by erosion of the upper peat laye and/or by transgression. The supply of material from the North Sea was not sufficient to keep up wich the rise in sea level over the whole of the Wadc Sea and the flats in the neighbourhood of the inlets received the greater p of the material. The shortage was felt chiefly in the area lying farthest landwards, that is the Pollen. The build up of the bed or formation of flat therefore lags far behind the increase in sea level. In addition, wave atta can be playing a part. With SW to N winds (the direction of gales) the area lies the farthest behind the sheltering row of islands so that the waves hea are high. Fine sediment (other sediment never settles in this area) is there fore easily brought into suspension and is then carried further by the curr This process does not occur exclusively at times of storm surges, because t bed is at 2 - 3 m below mean sea level and is soon disturbed by the movemer of waves.

In general, the behaviour of the channels corresponds quite clearly tc the movement of the water. In table 2 the results of flow measurements in a number of channels are presented. The lines along which discharge is measur are shown in fig 6. The measurements were performed in 1957 - 1959. By mear of this data and from measurements of hydraulic gradient, several factors h been calculated such as Chézy's coefficient C, the bed shear stress τ_{max}, the shear-velocity $u_{*\,max}$. These last two factors were calculated using the following formulae:

$$\tau = \rho g \frac{Q^2}{A^2 C^2} \qquad \text{Newtons/m}^2 \qquad (1)$$

$$u_* = \frac{\sqrt{g}}{C} \cdot \frac{Q}{A} \qquad \text{m/sec} \qquad (2)$$

where C = Chézy's coefficient in $m^{\frac{1}{2}}/sec$
A = cross sectional area in m^2
τ = bed shear stress in Newtons/m^2
ρ = density of water in kg/m^3
g = acceleration due to gravity in m/sec^2
Q = max. discharge in m^3/sec
u_* = shear velocity in m/sec

Further, at the end of the table, the type of bed material and the behaviour of the cross sectional area are described.

The influence of the external deltas.

The existence of an external delta at an inlet which is subject to strong tidal movement, is a common phenomenon. The external delta provides bridge for the littoral drift across the perpendicular flow in the inlet. I the transport takes place in the form of banks which erode on one side and accrete on the other and transplant themselves in their entirety across the

external delta. A cyclic process of this type can be observed in the delt the Inlet of Den Helder. However, the Noorder Haaks is here exeptional. T is presumably a very resistant bank which maintains almost the same posit The banks moving up from the south unite with the Noorder Haaks and from a flat makes the crossing of the northern channel of the delta and joins i self to the island of Texel.

To the south of the Noorder Haaks lie two channels: Schulpengat and Westgat. At the moment, the Westgat is being pushed against the Noorder H by the Zuider Haaks and is sanding up. The Schulpengat is therefore begin to take over the function of the Westgat and a new Schulpengat is being f along the coast of North Holland.

To the north of the Noorder Haaks lies one channel, the Molengat. Thi too is moving from south to north, under influence of the pressure of the bank which is moving from the Noorder Haaks to Texel. A former Molengat c be discerned in the Mok on Texel. The Onrust is a bank which has crossed c This course of events was shown by Ir.Grijm at the congress in Scheveninge in a film which was made by means of successive sounding charts.

The development of the Inlet of Vlie is much less clear. If it exist cycle here apparently takes much longer to complete.

However, the pressure of the eastern part of Vlieland is quite evide Because of this pressure, the inlet is being driven eastwards.

The western end of Terschelling, the "Noordvaarder", is a flat which united with Terschelling in about the 17th century. Old publications menti a navigable channel which connected with the North Sea directly to the we of the harbour of Terschelling.

The swinging of the channels in the external delta influences the ori ation of the channels on the inside of the inlet. The transport of sand is probably not the same during the various phases of the development.

The Eierlandse gat, between Texel and Vlieland experiences a similar course of events as the Inlet of Den Helder. Here there is only one main channel.

The cross-section of this inlet is increasing quite rapidly, probably a result of the shortage of sand in the external delta and a relatively sm littoral drift.

The development has apparently been influenced by the enclosure of th Zuider Sea. From 1911 to 1930, the cross sectional area oscillated about a value of 10.000 m^2; after 1930 it increased to 15.500 m^2 in 1960.

Future development.

The most important factors here are:
- the relative rise in sea level
- the transport of sand to the Wadden Sea
- coastal engineering

There is little known about the future movement of the sea level. Thi is dependent upon the climate on the earth and upon many other factors whe by the ratio of water to ice is altered. Observations over the whole earth indicate both rising and falling sea levels.

However, seeing that an important part of the relative rise in sea le is caused by consolidation of sediments and subsidence of the earth, it ca be assumed that the present movement will continue for the next few centur although perhaps at a different rate.

The amount of sand arriving will decrease because the Dutch and Belgi coasts are being increasingly protected against erosion by means of groyne In some places, harbour piers are being built far out into the sea (IJmuid Europoort) whereby the littoral drift is interrupted, at least for some tim

As long as the North Sea does not become shallower, no increased tran port of material from the sea bottom is to be expected.

The expectation is therefore that, if the present rise in sea level c tinues, the Wadden Sea as a whole will undergo little change. Owing to the shortage of sand, it is possible that the delay in response of the Wadden increase. The relative lowering and diminution of the flats which will acc pany this, can cause an increase in the capacity of inlets.

Local changes will continue to occur, especially in the area which is fluenced by the enclosing dam.

It is conceivable that in the distant future all the Wadden or a larg part of it will disappear and a region will be created similar to the pres day Pollen.

There are various reasons for wanting to terminate the existence of t Wadden Sea.

By closing the inlets, the coast line would be appreciably shortened. This would yield greater safety as well as economic advantages. The closur is technically possible especially now that in the Rhine delta so much ex perience will be gained in large closures.

The removal of the sand hunger of the Wadden Sea would cause the coas erosion along the North Sea to decrease. The external deltas would disappe and a clear coast would arise such as that of North and South Holland. Bec of this, it is possible that the heads of the Wadden islands, which now pr into the sea because they are sheltered behind the external deltas, would attacked and serious local erosion would occur.

Owing to the build up of the bed, the clay and peat layers of the Hol cene which still exist will be buried to increasing depths under new sea l If it is the intention to use the Wadden for agricultural purposes in the future, the closure of the inlets must not be delayed for too long.

A study of the soils in 1950 - 1952 showed that by means of deep plo on the flats between Den Helder and Wieringen, 64 % or 50 km^2 of clayey s heavier soil can be reclaimed and on the flats behind Texel and Vlieland or 120 km^2. If the sand were to continue covering the flats, these areas decrease.

At the moment there are no concrete plans for large civil works in t western Wadden Sea. Activity is temporarily diverted to the south, to the urgent closures in the Rhine delta.

The future will doubtless see the closure of the inlets of the Wadde Sea. This closure may be partial and may or may not be accompanied by wo

of reclamation.

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